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December 15, 2006

BY EMAIL AND OVERNIGHT DELIVERY

Amy Zimpfer
Associate Director, Air Division
U.S. Environmental Protection Agency
75 Hawthorne Street
San Francisco, CA 94105

Re: Cabrillo Port Project
Response to Information Request Dated October 13, 2006

Dear Amy:

By letter dated October 13, 2006, you submitted a series of detailed questions to BHP Billiton LNG International Inc. ("BHP") regarding its Cabrillo Port project. We responded to most aspects of your letter on November 3, 2006. However, there were several detailed parts to one of the questions relating to the BACT determination for the submerged combustion vaporizers ("SCVs") that BHP was unable to respond to fully at that time. Rather than delay the entire response, we answered the portions of that question that we could and committed to respond to the remainder of the question in December. This letter constitutes our response on the remainder of the question.

Question 4 of your October 13, 2006 letter requested further information regarding aspects of BHP's December 2005 control technology analysis. Specifically, you noted that while Cabrillo Port is not subject to either Ventura County APCD Rule 26 or PSD, that the company was voluntarily committing to utilize controls reflecting with what would be required if those programs applied. Consistent with that commitment, BHP provided to EPA an assessment of the controls that were appropriate for the project as part of the December 2005 addendum to the preconstruction permit application. In question 4 you requested that we provide additional detailed technical information about BHP's basis for concluding that selective catalytic reduction ("SCR") was not equivalent to BACT for Cabrillo Port and additional information regarding why CO catalysts are not considered safe for use on SCVs.

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In order to better answer your questions, BHP chose to engage an independent expert to review the viability of employing SCR at Cabrillo Port. SCR has never been used on SCVs located on a floating facility. BHP's engineering staff previously evaluated the feasibility of transferring SCR technology from a land based application to a marine application and concluded that it was not directly transferable. In responding to your October letter, BHP chose to obtain an outside opinion from the engineering company that did the design work for the one SCV installation that has employed SCR (i.e., Distrigas). Aker Kvaerner's ("Aker's") experience with the Distrigas project and other SCR projects make it uniquely qualified to provide answers to the questions that EPA posed. BHP provided Aker the questions posed by EPA and requested that they prepare a report answering them as completely as possible. Aker prepared a 30 page assessment with voluminous support data in response. A copy of that report is enclosed with this letter.

Aker reached several important conclusions after completion of its assessment regarding the state of SCR control on marine installations. First, Aker describes why the commercial availability of SCR for marine internal combustion engines is not relevant to whether SCR is commercially available for SCVs. They are different source categories because the technology is subject to significantly different demands. Aker goes on to note that extensive research and bench scale and pilot testing would be required before SCR could be transferred to SCVs located on a floating facility. The report evaluates the various technical and operational questions raised by EPA in light of the Distrigas experience and Aker's experience with SCR on other projects. This includes the space required for an SCR installation, the cost-effectiveness of SCR usage and the maintenance issues with maintaining the system aboard a ship. Aker's final conclusion is that at this time there is no reason to conclude that a marine SCR installation on SCVs would achieve a higher control efficiency when compared to the baseline emission scenario than the use of a lean pre-mix burner.

EPA has previously explained what it means for a control technology to be feasible. In the *New Source Review Workshop Manual*, EPA identifies that a control technology is feasible if it is both available and applicable. EPA notes that

> "A control technology is considered available, within the context presented above, if it has reached the licensing and commercial sales stage of development. A source would not be required to experience extended time delays or resource penalties to allow research to be conducted on a new technique. Neither is it expected that an applicant would be required to experience extended trials to learn how to apply a technology on a totally new and dissimilar source

> type. Consequently, technologies in the pilot scale testing stages of development would not be considered available for BACT review."

New Source Review Workshop Manual at B.18. The Aker report confirms that the use of SCR on a floating installation has not even reached the bench scale level of testing. Therefore, it is not available and cannot be considered a feasible technology. In short, SCR has not been achieved in practice and is not a technically feasible technology for the source category in which Cabrillo Port falls.

The Aker report carefully documents that SCR has not been applied to SCVs in Cabrillo Port's source category and that the technology is not currently feasible, as that term is used in determining BACT. The best control alternative is to use lean pre-mix burners in the SCVs. This will achieve a 50 percent NOx reduction as compared to conventional burners. Based on this control option, BHP believes that BACT for NOx is 20 ppmv.

I trust that this letter and the associated report and attachments fully and completely answers EPA's questions. Please contact me immediately if this is not the case.

Sincerely,

Thomas R. Wood

cc: Renee Klimczak
Rick Abel
Margaret Alkon
Joe Lapka

AKER KVÆRNER
Part of the Aker group

Technical Report

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Evaluation of SCV with SCR for Cabrillo Port FSRU

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BHP Billiton International Inc.

bhpbilliton

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1.0 Introduction

BHP Billiton has asked Aker Kvaerner (AK) to evaluate technical, design, environmental, operational, and economic questions associated with installing and operating Selective Catalytic Reduction (SCR) units on the exhaust streams of multiple Submerged Combustion Vaporizers (SCV) mounted on a floating storage and re-gasification unit (FSRU) for their Cabrillo Port Terminal. This study also addresses some of the specific issues and concerns raised by the EPA.

Aker Kvaerner was the design contractor for the first and only installation of an SCR treating exhaust gas of an SCV for Distrigas at Everett, Massachusetts. This is a land based unit started up in 2003, which was and is considered developmental. It has experienced difficulties in the hot exhaust gas ductwork, and blinding and fouling of the catalyst by carry over of sodium carbonate formed during neutralization of the water bath. Ongoing work at Distrigas has resolved some of these problems; however, issues with sodium carbonate carry over which is limiting catalyst life are still under investigation.

Recently Aker Kvaerner studied the use of SCR for treating exhaust from SCV units for an offshore facility located on fixed platforms. It was suggested that an alternate means of heating the SCV exhaust gas was needed to avoid problems experienced at Distrigas while providing for a safe operation. Unlike Cabrillo Port, which is a floating facility, this installation will be located on multiple fixed platforms in the Gulf of Mexico.

Combining SCR with SCV on a floating vessel has never been done. Based on Aker Kvaerner experience with the two earlier projects, the installation and operation of SCR in treating exhaust from the SCV on an offshore FSRU, such as Cabrillo Port will present many unique and complex challenges including sizing of the units, neutralization of the water bath, process performance due to the motion effect of the vessel, structural integrity and the unforeseen issues typical for "first of a kind" applications. For example, it is not known what effect the motion of the vessel will have on the performance of the SCR. Without such data it is impossible to predict the level of NOx reduction and thus the total NOx emitted into the atmosphere in the stack gas.

The sheer physical size of the SCR units and associated structural steel dwarf the SCV units they are installed on as a control device. Current layout on the FSRU is insufficient for accommodating SCR units without further extension of the ship.

Because of the many unique issues and necessary installation differences associated with controlling SCV emissions with SCR units in a floating environment, we believe that a floating installation must be considered a different source category from stationary or fixed platform based installations. It is our opinion that SCR is not a credible NOx control technology for SCV on an FSRU at this time as extensive bench and pilot scale testing would be required to design an SCR system that could function more effectively than the use of a lean pre-mix burner in a floating marine application.

2.0 Information Requested by BHP

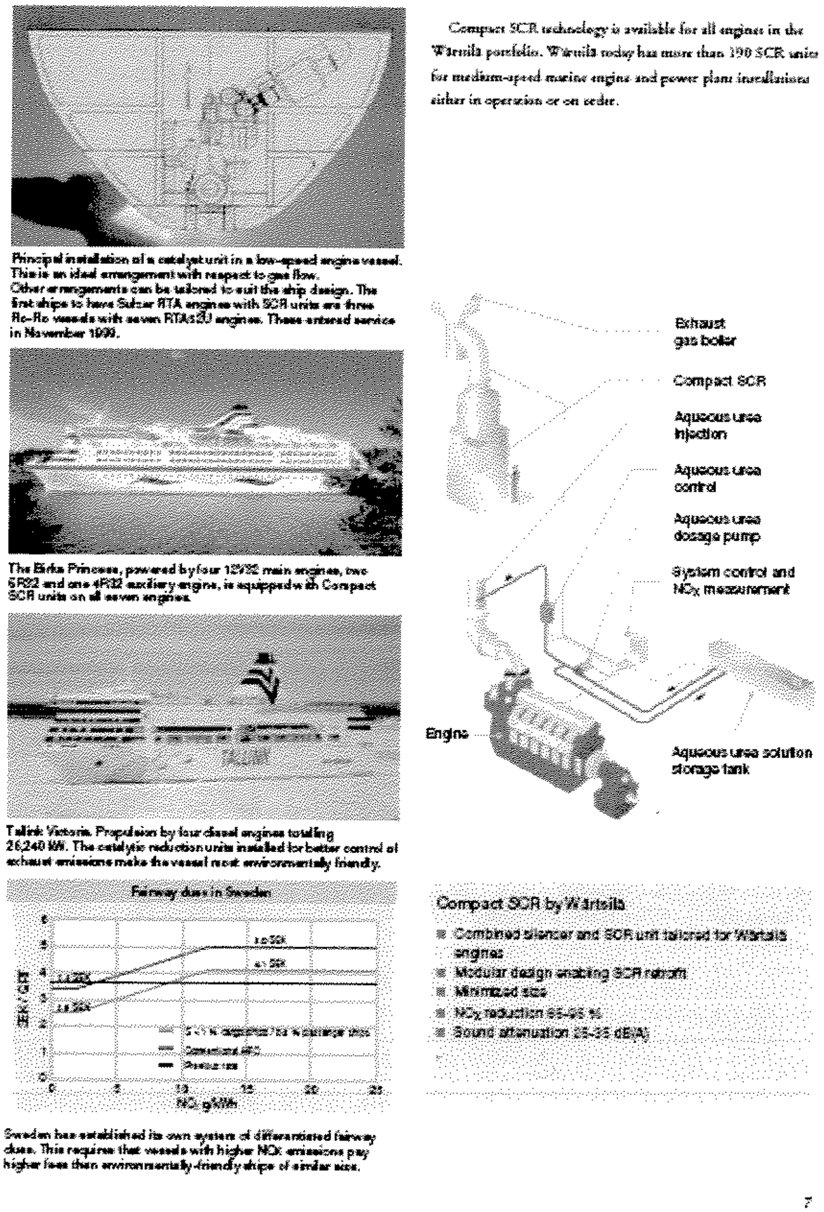
BHP has requested clarification and additional information regarding the use of selective catalytic reduction (SCR) and oxidation catalysts for the SCV on their FSRU. This information will be used to assess the best available control technology (BACT) for NOx emissions reduction from submerged combustion vaporizers in ship board (floating) applications. Specifically, the following factors listed below are addressed:

- Impacts related to the dynamic environment of a floating vessel
- The size and weight of the units and equipment layout
- Potential for catalyst blinding and fouling
- Options for heating the SCV exhaust gas to necessary temperatures
- Worker safety during control equipment operation and maintenance
- Cost effectiveness
- CO oxidation catalyst safety

2.1 Environment of a Floating Vessel

BHP has proposed an SCR system for NOx control from the Wartsila 9L50DF internal combustion engines (ICE). This is a marine duty, compact SCR unit mounted below decks in the engine room and supported by the ship's hull and structural members. A schematic of a typical installation of this type is extracted from the Wartsila EnviroEngine Concept brochure and shown in Figure 2.1 below. The complete brochure is included in Appendix C. This brochure identifies five different vessels currently operating with this type of SCR.

Figure 2.1 Wartsila Compact SCR for ICE



Refer to Appendix A, Munter Drawing 182V-2 for approximate size of an SCR in this application.

The SCR unit receives engine exhaust at high temperature directly into the catalyst beds mounted below decks. The “clean” gas is then exhausted directly to the atmosphere.

Placing the equipment lower in the ship reduces the mechanical effects of motion on the equipment and similarly reduces the effect of equipment weights on the hull stabilization. For example, a one degree roll of the ship will translate to about 0.32 ft of movement in the engine room. In comparison, this is equivalent to approximately 5 ft at the top of the platform of an SCR mounted on the SCV. The effect of the motion is much less in the engine room than that at the elevated part of the SCR units. The loads and stresses on the SCR units mounted on the ICE in the weather proof engine room are reduced. Also maintenance and operations are safer in this environment. In comparison, the relative motion for the SCR mounted on the open deck results in increased mechanical loads and stresses. With the exposure to wind loads and sea conditions, the SCR units and ducting will require additional supports and bracing.

SCR units mounted on ICE's are in use demonstrating the application on a floating vessel. Preliminary vendor drawings for such an SCR operating on a Wartsila 9L50DF engine indicate the dimensions (Lx W x H) are approximately 2,250mm (7.38') x 2,400mm (7.87') x 4,000mm (13.12'). The unit is estimated to weigh approximately 18,000 lb. Conceptual vendor design drawings for such a unit are included in Appendix C. At full load the exhaust flow from the engine is approximately 50,000 lb/hr. The mass flux is then 861 lb/hr/ft^2.

The use of SCR on an ICE is significantly different from the use of SCR on an SCV. The Wartsila engine exhaust gas is at a higher temperature (typically 700^{0}F-900^{0}F) going to the SCR unit. There is no requirement for large gas/gas exchanger and complex ductwork for preheating the exhaust as required in the SCR fitted to an SCV unit, where the typical temperature of the exhaust gas from the SCV unit is 60^{0}F -80^{0}F.

SCR units fitted to marine boilers, as proposed for Neptune Suez [(1)] and Northeast Gateway projects are standard units that can be installed on the boilers and do not require preheating of the exhaust gas prior to the SCR. These units are similar to the SCR units installed on the ICE. Moreover, the boilers are located below decks in the engine room with the same advantages mentioned above for ICE. Information received from Peerless indicates that the catalyst cross section for a unit mounted on a 300 MMbtu/hr boiler is about 250 ft^2, and the exhaust flow is 300,000 lb/hr. The mass flux rate is then 1,200 lb/hr/ft^2 which compares favourably with the SCR mounted on the engines. The SCR for ICE is generally designed to keep the back pressure low and therefore has a slightly lower velocity. The SCR unit for the boiler is estimated to weigh 100,000 lb. Although these are larger units (20' x 20' x12.5') than the SCR units on the ICE due to the difference in exhaust flow rates, only three of them would be required at this size (if utilized for supplying the equivalent heat of vaporization), whereas eight SCR units are required for the SCV application. There are a number of marine boiler suppliers that can provide standard packaged units fitted with SCR for emissions control; but there is only one manufacturer (BD Heat Division, Inc.) that has built an SCR for SCV units. This is a land based unit operated by Distrigas at Everett, Massachusetts in which Aker Kvaerner was involved in the conceptual design and engineering. Troubleshooting and subsequent operational issues were handled by BD Heat Recovery Division and Distrigas.

As mentioned above, preheating the SCV exhaust gases from about 60^0F-80^0F to 650°F - 700°F, is required before injecting ammonia into the SCR fitted to SCV units. This requires large heat exchanger(s), associated ductwork, and mixing with the hot gases prior to contact with the NOx reduction catalyst. Preliminary vendor drawings for an SCR operating on an SCV indicate the catalyst section cross section is approximately 8ft x 11ft. Conceptual drawings for such a unit are included in Appendix A (See Dwg. No. PGA1 - PGA3). At full load, one SCV (T-Thermal Model Sub-X 120) with lean pre-mix burner will provide exhaust flow of approximately 113,000 lb/hr. The mass flux is then 1,293 lb/hr/ft^2. It is apparent that an SCR unit designed for a boiler and an SCR unit designed for an SCV are designed for similar velocities and the SCR catalyst bed cross section is comparable. The primary differences in the SCR designed for an SCV are found in the counter flow two stage gas/gas exchangers, the large complex ductwork, gas turning and straightening sections and external heat source for the SCV exhaust gas. This accounts for the large size compared to the SCR units for ICE and marine boilers. The weight of such SCR unit designed to handle one SCV exhaust is estimated as 126,000 lb. and eight of these units are required for the Cabrillo Port facility, giving an estimated total weight well in excess of 1,000,000 lbs when additional structural members for strengthening the equipment and ductwork is taken into consideration on a moving vessel.

The unit at Distrigas is a large, vertically mounted installation with complex ductwork and gas/gas exchangers to facilitate heating the SCV exhaust gas to the SCR operating temperature of 650^0F-700^0F, and to recover part of the added heat [(2)]. These are much larger than SCR units for either ICE machines or marine boilers. Schematic drawings and a photograph of typical industrial type units are shown in Figures 2.2 and 2.3[(3)]. Conceptual drawings of the units that would be required for Cabrillo Port are found in Appendix A. (See drawings PGA1 – PGA-3).

Figure 2.2 Typical Industrial SCR Units for Low Temperature Exhaust
BD Heat Recovery Division, Inc. (3)

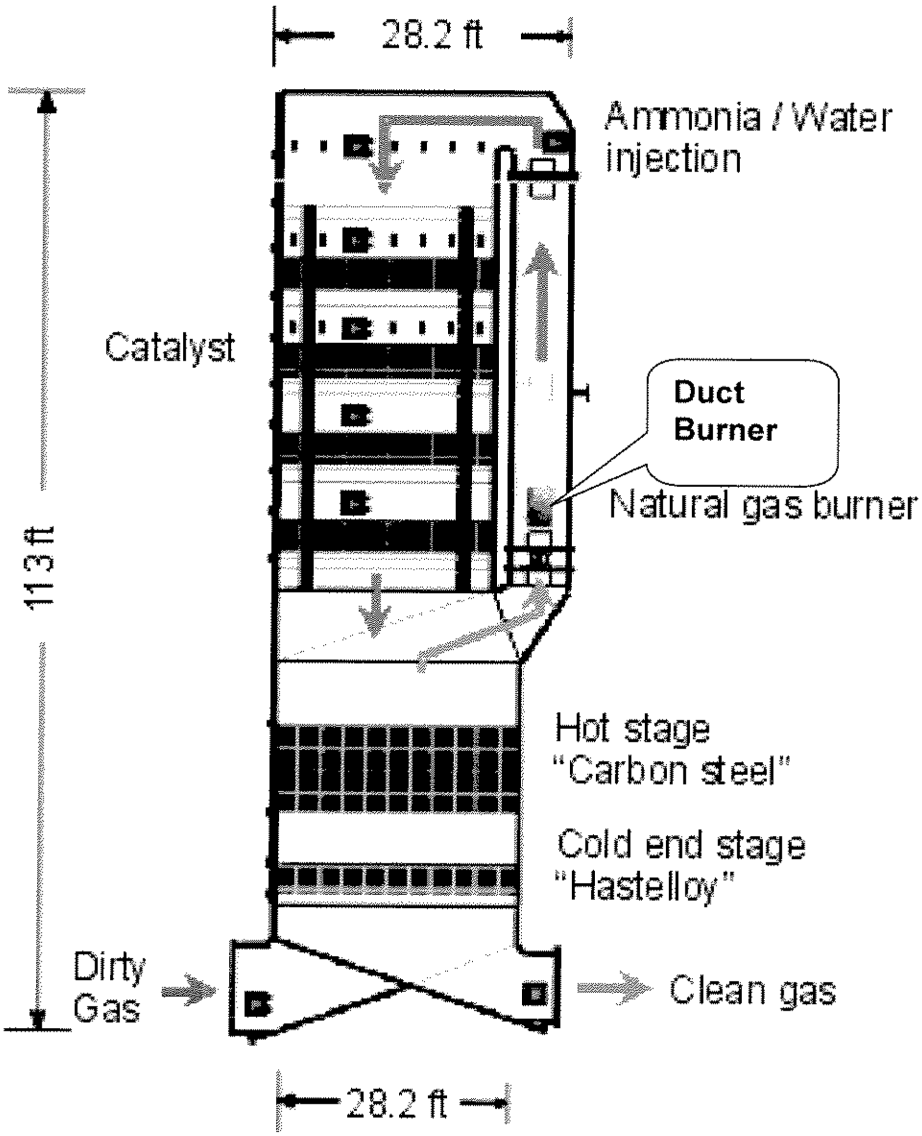
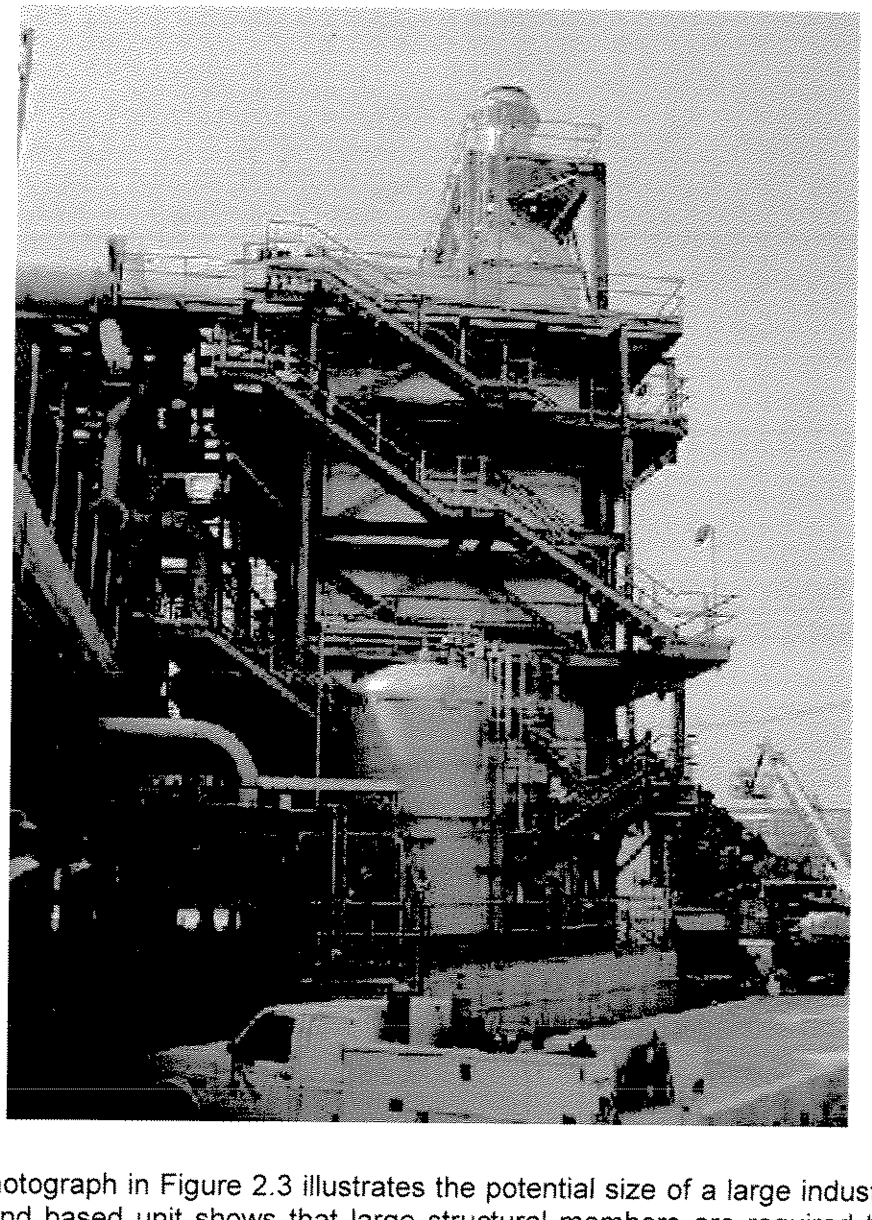


Figure 2.3 Typical Industrial SCR Units for Low Temperature Exhaust
BD Heat Recovery Division, Inc. (3)



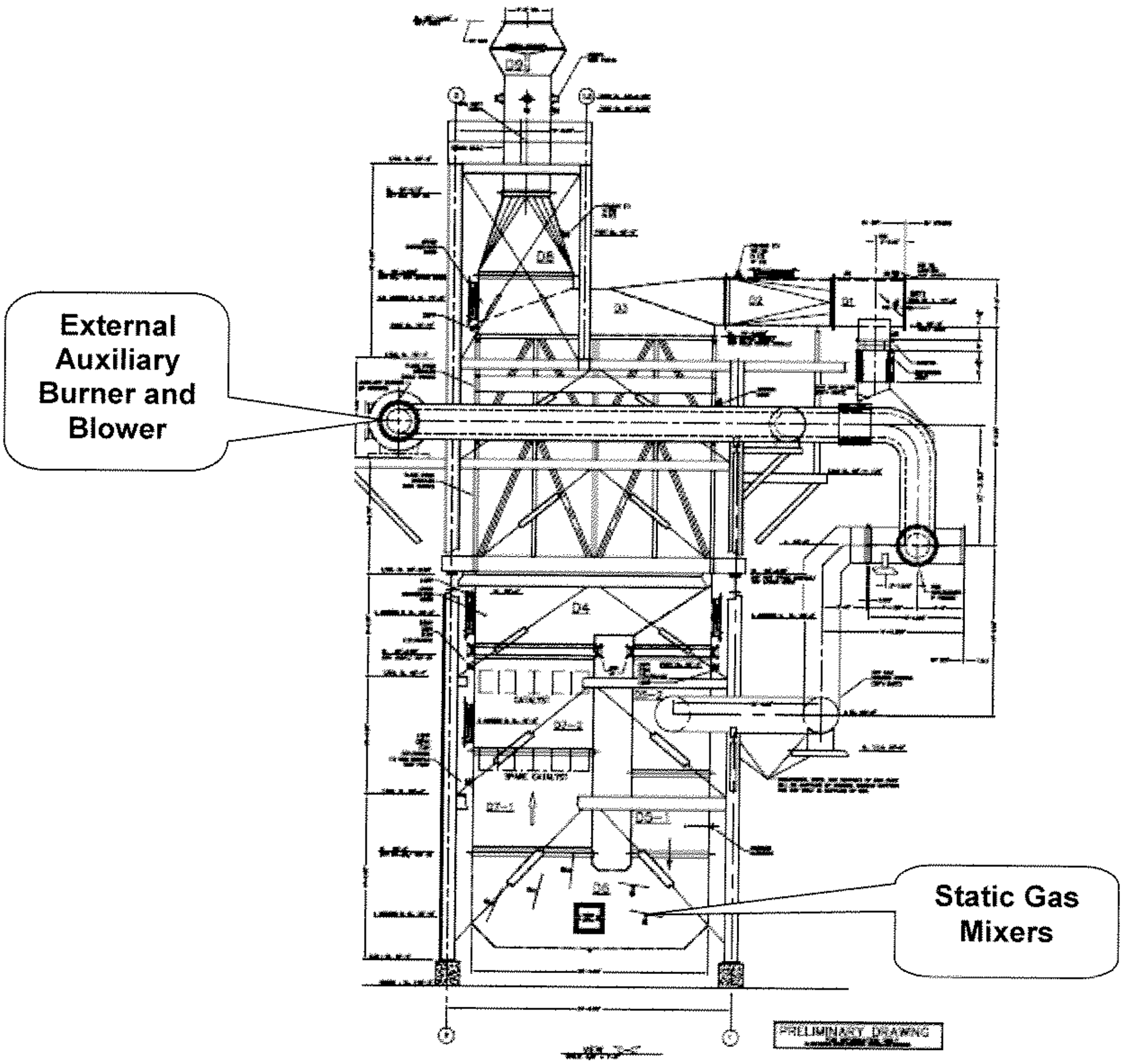
The photograph in Figure 2.3 illustrates the potential size of a large industrial SCR unit. This land based unit shows that large structural members are required to support the SCR unit. Applying a similar design to an offshore floating installation will certainly require more and thus heavier structural support to handle the inevitable motion of a ship.

Distrigas operates their SCR system at a land based facility, and most of their start-up and operational problems derive from two sources, the hot gas bypass and neutralization of the water bath [2]. Although the design can be improved to minimize these problems, these units are not "compact" and shipboard application of the technology in a motion induced atmosphere has not been demonstrated. Such SCR units on an FSRU will present a number of additional issues and challenges beyond those experienced by Distrigas.

The units would be mounted on deck, and preliminary layouts show that the units will rise approximately 82 feet above the deck, At this level; any movement of the vessel is amplified. It is unknown the extent to which the FSRU movement will interfere with the process performance, but effective removal of NOx relies on stable and consistent flow of exhaust gas from the SCV units and even distribution of NH_3 and exhaust gases across the catalyst beds. Even distribution and mixing of the gases is done with static gas mixers (SGM) which produce a vortex on the downstream side of the mixer, see Figure 2.5 for illustration. This is an aerodynamic device and the mixing efficiency resulting from the vortex formation will change as the angle of approach changes. The unit itself including the mixer will "tilt" as the ship moves, but the gas flow is not constrained to move with the SCR unit thereby changing the angle of approach as the vessel moves.

Figure 2.4 is the vendor's preliminary concept drawing showing the location of these mixers in the ductwork for the type of unit required for Cabrillo Port. The details of the preliminary concept drawing can be found in Appendix A (See Dwg. No. PGA1 - PGA3). The preliminary concept drawing includes overall duct work, external burners for supplemental heat requirements, heat exchangers to recover heat from the SCR exhaust, hot gas mixing at two locations (inlet and upstream of the ammonia injection point) the SCR catalyst beds, and associated mixers and other internals.

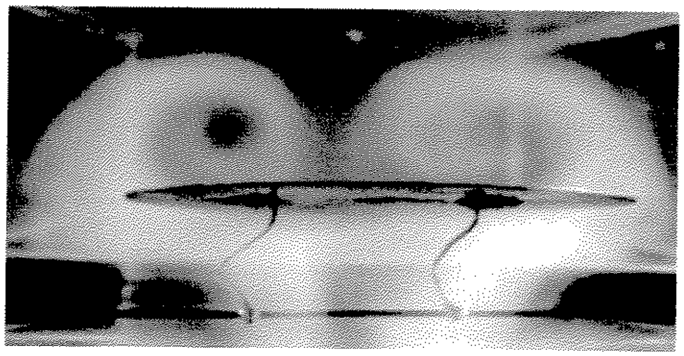
Figure 2.4 SCR for SCV unit (showing locations of Static Gas Mixers (SGM) and external auxiliary burner)



The paper presented at AIChE Spring National meeting in April 2004, "Operating Experience with an Integrated Selective Catalytic Reduction System (SCR) Operating with Submerged Combustion Vaporizers (SCV) at a North American Base Load Vaporization Facility", by David Hawkins, BD Heat Recovery Division, Inc. states:

"The static mixer utilizes the effects of a vortex produced when a disc or delta wing is positioned at a specific angle to a gaseous stream. There are several locations in the SCR system that uses the beneficial effects of this device."

Figure 2.5, Vortex Produced with Static Gas Mixers (2)



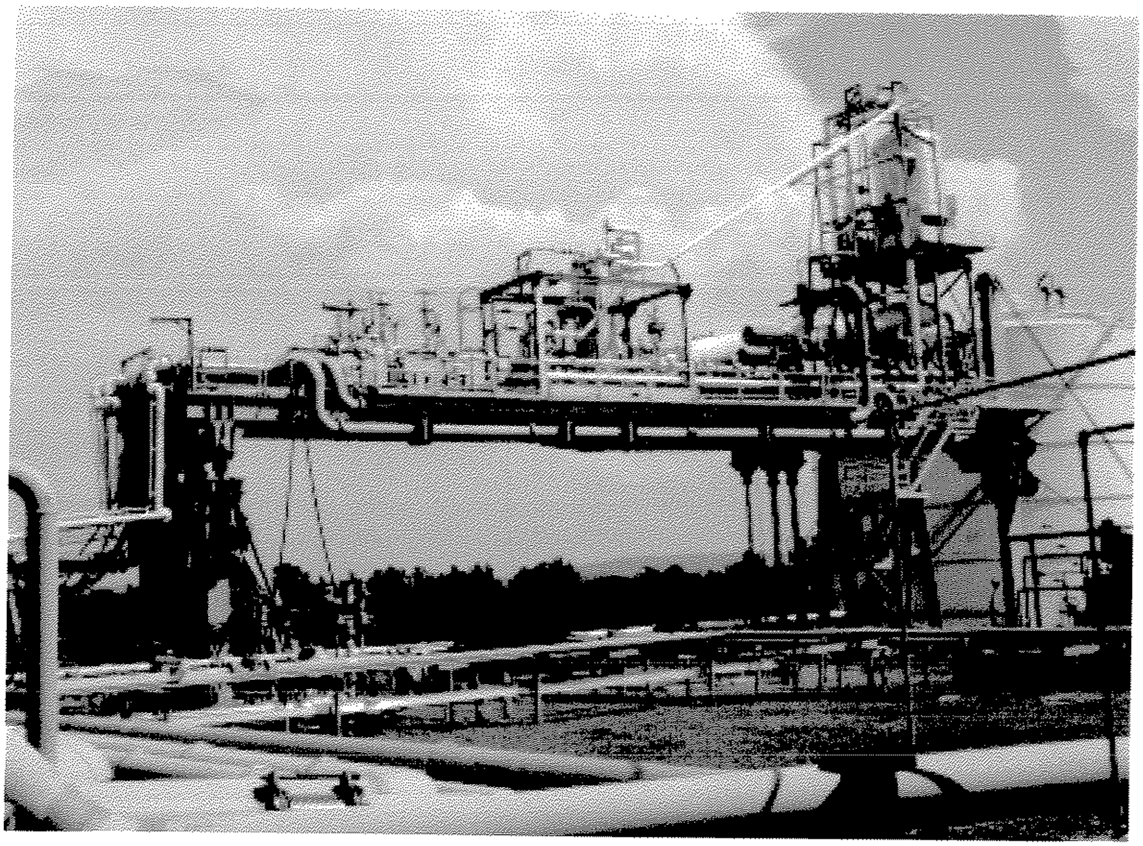
Although the Distrigas SCR units meet their expected performance, they are land based and have no motion sensitive effect. To the best of our knowledge, operating an SCV/SCR combination on the rolling, pitching deck of an FSRU has not been achieved in practice (AIP) since no such units have been installed and demonstrated on a floating vessel. Stable operation of an SCV, and thus the SCR, requires constant head on the burner, and that head is provided by water level in the bath. Movement of the ship will cause some movement in the water bath levels. Even though small, the "sloshing effect" could potentially cause the head on the burner to vary, thus introducing instabilities in the flow, composition and distribution of the SCV exhaust.

These issues cannot simply be "designed around" because there is little or no data on which to base the FSRU design. Evaluating the performance of the SGM in a dynamic situation will require an extensive computational fluid dynamics (CFD) analysis.

Determining the effect of motion on the operation of the SCV and SCR units will require overcoming design challenges associated with operating them on an FSRU and a pilot program would be necessary. Only after operation of a pilot program for a reasonable time period would it be possible to predict the performance, stability and safety of these SCR units. To provide the necessary confidence level and to prove the feasibility of this technology for FSRU, it will be necessary to set up a pilot or full scale test facility with the SCV and SCR mounted on a moving platform. Testing is part of proving the concept. Proceeding with the project prior to testing and validation of the results introduces significant risk in capital cost and schedule to a project. This is clearly in the realm of research and development and cannot be considered available technology for an FSRU application.

One example of a similar approach is the Excellerate Energy Bridge project wherein the project team conducted full scale test of the vaporizer equipment on a movable platform to simulate the anticipated range of vessel motion [13]. The test facility is shown in Figure 2.6 below. As can be seen, a considerable amount of money was spent ensuring that the technology which worked in an onshore environment would actually work in a marine environment. A similar approach is likely to be needed to prove the concept of an SCR treating exhaust from an SCV in a ship mounted environment.

Figure 2.6 Test Facilities for Excellerate Energy Bridge
OTC 17161, September 2003 [13]



2.2 SCR Size and Weight

Notwithstanding the term "Compact SCR Unit" these are large units in industrial applications. Heating the SCV exhaust gas to the SCR operating temperature of over 600^0F requires large exchangers, complex ductwork and high temperature heat input. Extra consideration and equipment is needed to design a heating system that is both functional and safe in the event of a tube failure in the SCV containing LNG.

The effect of the additional weight associated with the SCR units will impact the overall deck and hull weight. This effect has to be evaluated in detail during the design of the hull and the real impact cannot be fully understood without detailed analysis.

The conceptual drawings by BD Heat Division, Inc. for Cabrillo Port included in Appendix A, show SCR units with a footprint of approximately 24' x 41.5', and a height of 82' above the deck. This does not include the large, complex ductwork required to interconnect the SCV and SCR or to connect the auxiliary burner for heating the SCV exhaust. These drawings contemplate one SCR servicing two SCV units; however, one SCR per SCV or one SCR unit between two SCV units may affect operational uptime, which needs to be evaluated in a reliability analysis for FSRU. Based on current work performed for a fixed structure offshore SCR unit with SCV, we believe that the most appropriate design is one SCR for each SCV for reliability purposes. This is based on the experience at Distrigas on frequency and downtime required for catalyst change out. Distrigas experienced significant unplanned downtime as the result of having to shut down two SCV units each time the maintenance had to be performed on an SCR unit. A key lesson learned from that installation is that a 2 on 1 design of this sort is not practical. This is particularly true in relation to an offshore installation where parts and service must come from onshore and it takes a greater amount of time to complete basic maintenance tasks due to space and manning constraints.

Structurally, the SCR units will be subjected to forces associated with vessel motion that are beyond those experienced in a land based plant. This results in implications affecting center of gravity, space requirements, equipment layout and wind resistance to name a few. All of these will affect the vessel's design. The ships structure would need to be reinforced to handle the added weight and space limitations will require the hull to be lengthened to accommodate the additional equipment, piping and ancillary equipment. Currently, the Cabrillo Port FSRU design lacks available space that could accommodate this equipment.

The referenced article "Lower Emission LNG Vaporization", Dr. C.C. Yang and Dr. Zupeng Huang [5] which was used by the EPA as a reference to stability of SCV operations stated that:

"For SCV operation, since the thermal capacity of the water bath is high, it is possible to maintain a stable operation [LNG flow] *even for sudden start-ups/shutdowns and rapid load fluctuations. Thus, they provide great flexibility for quick start-up after shutdowns and the ability to quickly respond to changing demand requirements."*

This statement is in reference to land based SCV units without an SCR fitted. The comment in the reference seems to apply more to the stability of LNG flow and gas send out rather than the stability of the SCV exhaust gas flow that is relevant to the operation of SCR. It does not consider either ship board SCV units, SCV units with SCR or the compounded problems of combining these two elements.

The article includes CV's for both authors, and there is nothing there to suggest that either has experience designing or operating a combined SCV/SCR unit. More authoritative sources are those who have designed these units (BD Heat) and those who have operated those (Distrigas) and dealt with the problems on a day to day basis [(2)].

2.3 Equipment Layout

Preliminary layouts have been developed to determine if the available space is sufficient to add the SCR units. The preliminary layout studies indicate that the hull will need to be extended about 30 meters to accommodate the equipment, piping and ancillary equipment needed to include SCR units. The Figures 2.7 and 2.8 provide layout for the SCV with SCR combination and a comparison sketch showing SCV with and without SCR. The detail layout drawings are located in Appendix A of this report. As a point of reference, Aker Kvaerner recently completed concept design studies for SCV/SCR units on a fixed offshore platform. This design included eight SCV/SCR units requiring in excess of 30,000 ft^2 of deck space. The space allocated for the vaporizers in the existing Cabrillo Port design is 16,400 ft^2. Adding the 30 meters of length will double the space (puts the available deck space at 32,500 ft^2), which is consistent with the space requirements for the fixed platform. To confirm the requirements, additional layout studies are required incorporating safety and operability in FSRU unit. The side elevation of the potential SCV/SCR installation for Cabrillo Port is also included in Appendix A, and the top of the SCR stacks is at an elevation near the top of the vent stack.

The personnel access platform near the top of the SCR stacks is at an elevation much closer to the top of the high and low pressure vent stacks than the SCV and other equipment requiring personnel access in the design without SCR units. This proximity to the vent stacks would present a potential safety issue. Since the ship would normally "weathervane" about its mooring such that the wind blows from the bow of the ship toward the stern, personnel working on the SCR at these levels (which is downwind from the vent) may potentially be exposed to a release of cold hydrocarbon gas during an emergency venting situation. The location and height of the existing vent system may need to be redesigned in view of the safety implications.

As discussed above, a layout combining exhaust from two SCV units into one larger SCR unit was investigated. Combining two SCV units exhaust into the single larger SCR unit provides some economic and space optimization, but it will lower the overall reliability factor for the terminal as shutting down an SCR will necessitate shutting down two SCV units. Based on the experience at Distrigas, this 2 on 1 configuration is no longer considered a technically sound option. Therefore, consistent with our work on another project the design is based on having individual SCR units for each SCV.

A horizontal SCR combined with an SCV was also considered. The preliminary horizontal SCR design indicates lower plot space requirement in comparison to the vertical SCR unit, but additional safety and operational considerations are required before reaching any firm conclusion. However, this option is not considered further because there is no known existing horizontal SCR unit in operation for treating the SCV exhaust.

All scenarios indicate that the addition of SCR to the SCV units will have a significant impact to the size, stability, serviceability and reliability and will significantly increase the capital and operating expenses for the FSRU. Although SCV/SCR units have been proposed for fixed offshore platforms, these are not subjected to the movement present on an FSRU. This motion introduces considerable uncertainty regarding operability, maintainability, reliability, effectiveness, and safety. Further research and testing is necessary to confirm or predict the performance of SCV/SCR combinations. For these reasons, the combination of SCR with SCV should not be considered to have reached the licensing and commercial demonstration stage for NOx abatement aboard an FSRU.

Technical Report

Figure 2.7 Layout Sketch for SCV with SCR units

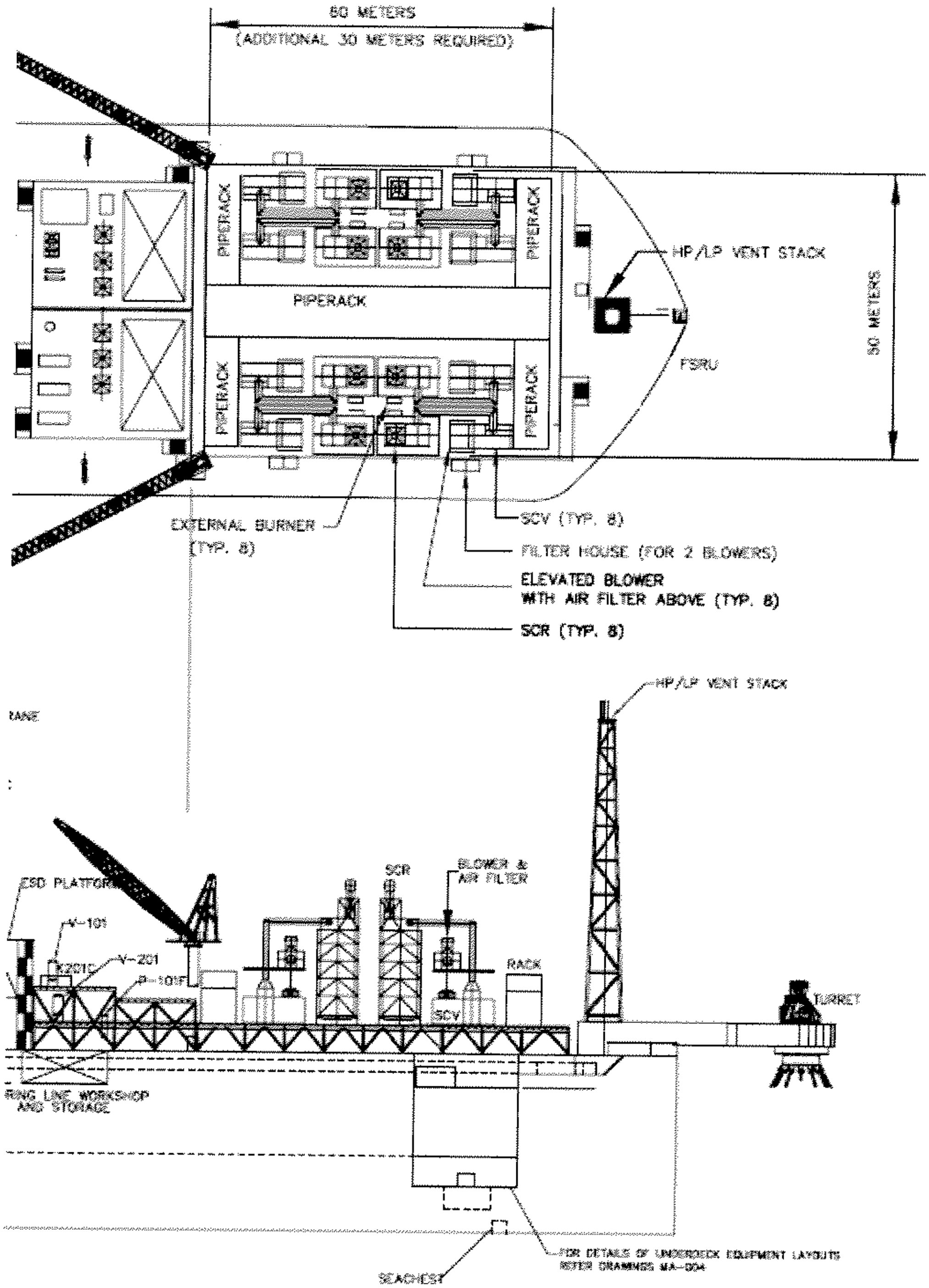
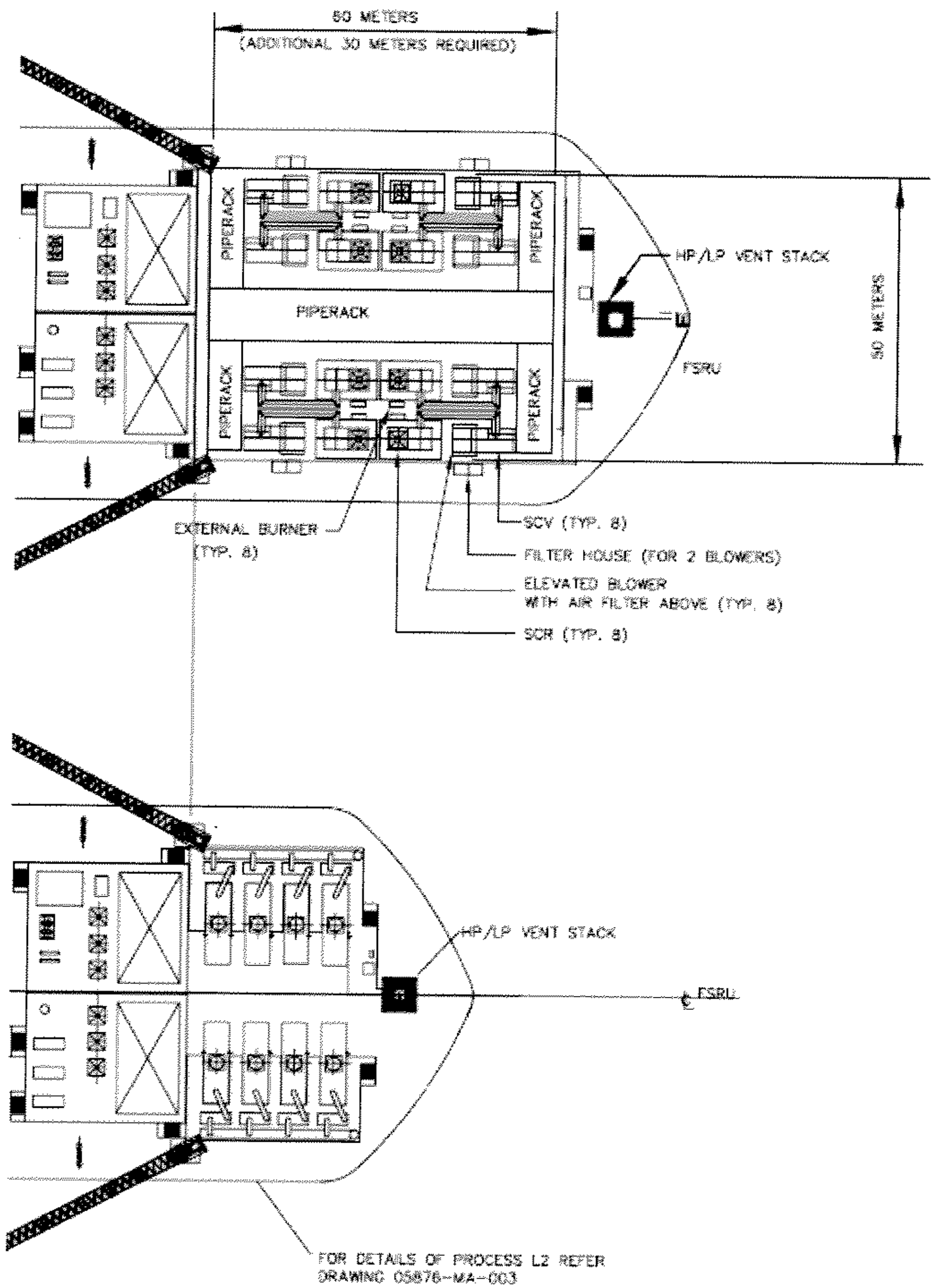


Figure 2.8 Comparison of layout for SCV With and Without SCR units



2. 4 Catalyst Blinding

With respect to salt spray, salt water and salt entrained in the air around the FSRU is not a large issue for the ICE machines, it could be a concern for the SCR on SCV units. It is well known that sodium will poison the SCR catalyst. While this is a concern offshore and proper air filtration is required, this does not seem to affect SCR units for the ICE marine engines as the ICE SCR units are normally mounted below decks. The air intake manifolds are in the engine room and air quality can be more closely controlled. The SCR units for the SCV are mounted above the deck and are exposed to the weather and potential sea water spray coming over the decks. The air intake manifolds for the external auxiliary burners that supply supplemental heat to preheat the exhaust gas, prior to entering the SCR, has a potential for salt carry over from the salt spray on the deck. While all efforts are made during the design and selection of the air intake filtration equipment to minimize the impact of salt carry over to the SCR catalyst bed, the ship deck, unlike the ship engine room, is not in a controlled environment and there is a potential for salt carry over to the SCR bed through the external burners air intake.

Additional research and design work is necessary to avoid catalyst poisoning from sodium generated within the SCV system as experienced by Distrigas. Neutralizing the SCV water bath is normally done with sodium hydroxide, or sodium carbonate. At Distrigas, sodium carbonate or "soda ash" is used to neutralise the acidic SCV water and part of the neutralised water (containing sodium carbonate) is injected into the burners for NOx control. The carryover of this water via the hot gas bypass into the SCR may have contributed to the SCR catalyst poisoning. Distrigas initially had and continues to experience problems with sodium poisoning of their catalysts as evidenced by the following quote from recent communications with BD Heat Recovery Division, Inc.

"The sodium both poisons and masks the catalyst. Sodium will block the acid sites on the catalyst and prevent ammonium from adsorbing. But at Distrigas there is so much that it actually lays down on top of the catalyst as well, like fly ash in a coal fired boiler. We have therefore also suggested they look at using both catalyst layers and use a more open pitched catalyst. This may be used in the future." (7)

The life of the catalyst in the Distrigas units is currently less than one year based on recent discussions. (14)

Additional discussions on this problem and potential solutions are presented in section 2.5 of this report. The exact cause of the ongoing catalyst poisoning has still not been isolated and remedied; however potential solutions are being evaluated.

The suggestion that Distrigas overcame its catalyst poisoning problem by using ammonia as a neutralizing agent instead of sodium carbonate is not accurate. We understand that EPA was informed that Distrigas had a catalyst poisoning problem that was resolved by using ammonia as a neutralizing agent. We are not clear where EPA obtained the information that Distrigas was using ammonia as the neutralizing agent in place of sodium carbonate, but this belief was confirmed as incorrect by Distrigas' engineering manager on November 30, 2006. (14)

As mentioned above, Distrigas is still working to overcome its catalyst poisoning issue and is trying to minimize the sodium that makes its way from the SCV units into the SCR system. BD Heat has suggested in a paper [(2)] that another step to try would be the use of ammonia for neutralizing acidic water and pH control in the SCV unit to minimize the catalyst poisoning associated with sodium salt carry over from the water bath;[(2)] however, ammonia has never been used at Distrigas as a neutralizing agent for the SCV water bath [(14)]. Moreover, water from the bath is injected into the burner to cool it for NOx reduction, if utilized ammonia is liberated in the high temperature sections of the burner and will combust directly to NOx as fuel nitrogen in the burner, thereby increasing NOx production. It is not clear what unanticipated impacts would arise from the use of ammonia as a neutralizing agent and the carryover of the resulting ammonium carbonate.

2.5 Heating of SCV Exhaust Gas

The safety issues associated with a gas leak in the SCV tubing is a concern in the design of a SCR unit. The Distrigas design includes a hot gas bypass from the SCV burner for heating low temperature SCV exhaust. The high temperature exhaust was used in the design to address this specific safety issue and provide an inert atmosphere in the SCR unit. The hot gas bypass has presented a number of mechanical issues including catalyst blinding as described previously in Section 2.4. In addition, water injected into the SCV burner found its way into the hot gas bypass line and was carried over into the SCR. The sodium carbonate in this water contributed to blinding the catalyst. The water also damaged the internal insulation in the hot gas bypass, causing the internal insulation to be released from the duct wall and plugged the catalyst beds [(2)]. Aker Kvaerner considered a design with an indirect burner in combination with a separate gas/gas heat exchanger to heat the cold SCV exhaust and mitigate the risks associated with the direct duct burners. Auxiliary burners making hot air to heat the SCV exhaust through an auxiliary "gas/gas exchanger", will significantly increase the size and cost of the units for FSRU.

Duct burners are also an option. Figure 2.2 above shows the typical location of a duct burner in an SCR unit. It is located in the ductwork between the gas/gas exchanger and the catalyst beds; however, this is a schematic of a typical unit, not necessarily for an LNG vaporizer. The fear with a duct burner is the likelihood of a fire in the event of a gas leak from the tubes into the SCV exhaust.

Another method is to heat the exhaust with hot gas generated in an external auxiliary burner and injected into the SCV exhaust stream. Appendix A provides compact DeNOx system general arrangement drawings (PGA1-3) from BD Heat Recovery Division, Inc. Figure 2.4 shows the location of hot gas injection from an external auxiliary burner for heating the cold exhaust from the SCV unit. From a cost, size, and safety standpoint, this is the preferred method of heating the exhaust gas prior to the SCR catalyst beds. Keeping a positive pressure in the auxiliary burners installed separately outside and connected through its own duct system to inject hot gas into the main duct will help prevent migration of any gas to the auxiliary burners in case of leaks in the SCV tubes. The hot gas injected into the exhaust should be maintained below the autoignition temperature of methane. Adding auxiliary burners to the system will require additional space on the FSRU.

Regardless of methods utilized for heating the SCV exhaust, safety issues can still arise from a gas leak from the SCV tubes. Such a failure presents additional explosive hazards since the leaking methane is within a large confined space. Pilot scale testing is required to ensure that adequate positive pressure can be maintained by the system under all FSRU operating conditions. Additional discussion is provided related to CO oxidation catalyst safety in section 2.8 below.

2.6 Worker Safety

Aker Kvaerner, and to the best of our knowledge, all the operating companies policies such as BHP Billiton, always provide for worker safety and well being through diligent design, safety reviews, training and procedures. Worker safety will always influence the choice of technology and the equipment or process design. If the equipment, as designed, is not considered safe to operate and maintain, then the equipment cannot be considered technically feasible and would never become commercially available.

Catalyst replacement will be required for the SCR units. Based on the current experience at Distrigas, the catalyst life is expected to be less than one year [14]. As mentioned earlier in Section 2.1, these units are very large and platform access to the SCR on an FSRU is at a high elevation and will pose worker safety issues during the operation. These safety issues must be considered and analyzed in the design and operation of the SCR specific to FSRU. Key components of design and operation of an SCR unit installed on an FSRU are adequate service access, adequate worker safety and adequate operational reliability. These considerations will have to be specific to a floating installation due to the substantial differences between onshore and offshore applications.

2.7 Cost-Effectiveness

Improved air and fuel control to the SCV conventional burner provides better control of NOx and CO production in the burner than previous models. T-Thermal Company provided an equipment specification to Cabrillo Port stating that with the lean pre-mix burners would have guaranteed NOx emission levels of around 20 ppm. [9] Aker Kvaerner understands that EPA has directed BHP Billiton to consider cost-effectiveness for NOx controls against a 40 ppm uncontrolled emission rate and incremental cost-effectiveness against the 20 ppm lean pre-mix burner emission rate. The cost effectiveness analysis for NOx removal with SCR units was calculated using the EPA Office of Air Quality Planning and Standards methodology for Cost Effectiveness. The results are shown below in Table 2.1. The complete output from the spreadsheet is included in Appendix D.

Table 2.1, Cost Effectiveness for NOx Reduction

	Average	Incremental
NOx @	40 ppmv	20 ppmv
NOx produced, tpy	97.85	48.93
NOx @ 5 ppmv, tpy	12.23	12.23
NOx Removed, tpy	85.62	36.70
Cost Effectiveness, $/ton NOx removed	$173,496	$404,760

In calculating cost effectiveness, a post-control NOx level of 5 ppm was used solely because this has been achieved at the Distrigas facility. As discussed above, there is no basis for assuming that SCR for SCV units on an FSRU would achieve this control level. Since there is no data available for this specific application, Aker Kvaerner is uncertain that the SCR system would achieve better results than use of lean premix burners for SCV in FSRU application.

It is assumed that two additional personnel at $340,000 per year are required for operation and maintenance of the SCR units. The 30 meter FSRU extension required to accommodate eight SCR units is estimated at $30,000,000. Details of this estimate are included in Appendix D.

We are aware of only one manufacturer who has designed and built these units (BD Heat Recovery Div., Inc). There is only one land based application in operation at this time and none on an FSRU. We have asked for a budget cost of these units and have not received it as of this report issue date. However, for budgetary purposes we used a base capital cost of $12,000,000 (for the 8 SCR units) based on Aker Kvaerner's in-house data on a previous project. Operating expenses were based on established cost multipliers and cost information from other projects. In our opinion, the operational cost should consider 2 additional workers (instead of the 8 additional workers previously suggested) on the average for operation and maintenance of the SCR units.

The increase in size of the FSRU will require additional layout study and analysis in piping and other systems as mentioned in the earlier section of the report. We recommend that a proper layout and cost analysis be performed in the subsequent phase of this study if SCR units are considered for the SCV. A 5% contingency has been provided in the cost effectiveness calculations, but it is expected that the detailed cost estimate for a marine type offshore SCR/ SCV unit may exceed the costs used in this analysis.

As noted above, T-Thermal stated that the lean premix burners will produce less than 20 ppm NOx [9]. Based on these results, we suggest the need for an SCR unit be re-evaluated. The lean premix burners give a 50% reduction in NOx emissions as compared to the 40 ppm baseline emission level requested by EPA. There is a lot of uncertainty that SCR for SCV units located on the FSRU would be capable of meeting this control level based on the information available at this time. Elimination of SCR in favor of use of the lean premix burners has the added benefit of eliminating ammonia slip from the SCR, eliminating the annual catalyst replacement and maintaining a smaller and lower FSRU profile. These appear to be material considerations suggesting that SCR may not be the optimal means of NOx control for SCV on the FSRU.

2.8 CO Oxidation Catalyst and Safety Issue

Information received from catalyst vendors indicates that CO oxidation catalysts (CATOX) will not readily initiate an oxidation reaction with methane; however, it is possible [(10)].

Assuming that each CATOX / SCR unit handles one SCV, the exhaust flow would be approximately 113,000 lb/hr at full load with the following composition.

Component	Mol%
CO2	8.50
H2O	3.44
O2	5.08
N2	82.01
Ar	0.97

The impact of a tube leak resulting in ignition of the methane by the oxidation catalyst depends on the size of the leak. The worst case would be a small leak of about 3,300 lb/hr. This is the amount of methane required to reach the lower flammability limit (LFL) of methane in the exhaust gas. A smaller leak would not provide enough gas to reach the LFL, and ignition can take place only in the flammable region. Based on information from a catalyst vendor, it is unlikely that the CO oxidation catalyst would initiate an ignition; however, it is possible and the catalyst would be listed as a potential ignition source on the suppliers MSDS. Several simultaneous events would need to occur to get ignition.

1. A gas leak would need to occur in the vaporizer tubing.
2. That leak would need to put the exhaust in the flammable region.
3. The oxidation catalyst would need to oxidize enough gas to generate a hot spot greater than the autoignition temperature of methane.

A leak of about 11,000 lb/hr exceeds the upper flammability limit of methane in the exhaust. Ignition could occur between these two rates (3,300 – 11,000 lb/hr). Both of these are relatively small leaks in that complete rupture of a 1" tube would flow about 135,000 lb/hr [(11)]. Appendix D provides temperature calculations for various methane tube leak rates as well as the theoretical maximum temperature in the exhaust in the event of an ignition. These calculations anticipate that all of the oxygen is consumed in a fire; however, the minimum oxygen concentration (MOC) that will support combustion of methane is about 2.5%.

CO Oxidation catalyst is not used at Distrigas, and we know of no other installation in operation at this time where CO oxidation catalyst is used in conjunction with an SCV unit.

3.0 Conclusions and Recommendations

The following conclusions and recommendations are made based upon this study and Aker Kvaerner previous experience with SCV units equipped with SCR.

3.1 Although marine SCR is proven and is in use to remove NOx from ICE and boiler exhausts on board ships, these units are very different in configuration, size and weight from that required for NOx abatement from an SCV exhaust.

3.2 Distrigas has proven that it is possible to remove NOx from an SCV exhaust, but the unit is large (vertically mounted) with complex ductwork and gas/gas exchangers to facilitate heating the SCV exhaust. At this time, the land based existing unit is still undergoing development after 3 years of operation.

3.3 The design, installation and operation of an SCR/SCV combination on a floating vessel have never been done. It is problematical, unproven, and will require significant analysis and testing to be assured that gas distribution in the SCR can be maintained, and that stable operation of the SCV water bath and burners can be achieved in a dynamic (pitching, rolling) environment such as will be encountered on an FSRU.

3.4 The SCR units required for the SCV service are large, vertical units which will extend approximately 82 feet above the deck negatively affecting centre of gravity, space requirements, equipment layout and windage and many other areas. All of these will impact the vessel's size and stability. Structurally, the units will be subjected to forces induced by vessel motion and will be different from those experienced in a land based plant. The result is that the land based technology is not directly transferable to a floating operation without further research, analysis, design, and testing work.

3.5 Preliminary layouts have been developed which show that space on the vessel is insufficient to add the SCR units. The vessel hull length will need to be extended by about 30 meters to accommodate the SCV/SCR units, piping, ductwork, electrical, instrumentation and ancillary equipment. Further equipment design and layout studies are required to accurately size the vessel, but 30 meters should be considered a reasonable minimum that the FSRU would need to be extended, based on a comparison with existing layout studies that Aker Kvaerner has done on SCV/SCR units for fixed platforms.

3.6 Catalyst blinding and poisoning is an ongoing issue at Distrigas due to the use of sodium carbonate for pH control in the SCV water bath and sodium carbonate carryover from the SCV bath. Ammonia has been suggested for neutralizing the water bath, but Distrigas informed us that they have not tried this approach. Therefore, this approach has not been tested and there is no data as to what other unforeseen consequences could result from the use of ammonia.

3.7 Heating the exhaust gas from an SCV is necessary for SCR to operate. Typical units of this type, in other applications, use duct burners to heat the gas before flowing to the catalyst beds. In an SCV, the potential for tube leaks into the water bath is a safety risk. Options that may be more suitable for SCR's operating on SCV units are indirect gas/gas heat exchange or external auxiliary burners. In either design, additional equipment will be required to assure safe operation.

3.8 The SCR units will have maintenance platforms near the top, and movement of the ship will be amplified at these heights. With greater safety risks when working at height to replace catalyst, workers will require specific training and equipment for working in this environment.

3.9 Upper level maintenance platforms on the SCR units will be near the top of the high pressure and low pressure vent stacks. Since the vessel will typically weathervane into the wind, the height and location of the existing vent stacks may need to be redesigned to consider safety of personnel working at these levels who may be exposed to a potential release of hydrocarbon gas.

3.10 T-Thermal states that they can guarantee 20 ppm of NOx from their lean premix burners and EPA has directed BHP Billiton to utilize 40 ppm of NOx as the baseline value. Based on NOx removed from 40 ppm to 5 ppm concentration, the average cost effectiveness of SCR is calculated as $173,496 per ton of NOx removed. This operating cost includes two (2) additional personnel. Based on NOx removed from 20 ppm to 5 ppm concentration, the incremental cost effectiveness of SCR is calculated as $404,760 per ton of NOx removed. Aker Kvaerner evaluated cost-effectiveness in relation to 5 ppm because that was achieved by Distrigas; however, there is no basis at this time to conclude that a marine application for FSRU could achieve this level of control given the physical challenges to the SCR system for SCV and the ongoing operational issues at Distrigas. Elimination of SCR in favor of lean premix burners brings the added benefits of eliminating ammonia slip from the SCR, eliminating the annual catalyst replacement and maintaining a smaller and lower FSRU profile. These appear to be material considerations suggesting that SCR may not be the optimal means of NOx control for SCV on the FSRU.

3.11 Information received from catalyst vendors indicates that CO oxidation catalysts will not readily initiate an oxidation reaction with methane; however, it is possible. A methane leak of 3,300 – 11,000 lb/hr could put the flue gas in the combustible range. These are relatively small leaks compared to a complete tube failure. The leak rate from a complete tube failure will probably cause the fuel concentration to exceed the upper flammability limit.

3.12 As explained above, our opinion is that SCR is not a credible NOx control technology for SCV on an FSRU at this time as extensive bench and pilot scale testing would be required to design an SCR system that could function more effectively than the use of a lean pre-mix burner in a floating marine application.

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4.0 Appendices

Appendix A Drawings and data sheets

Appendix B References cited in the report

Appendix C Brochure for Wartsila Internal Combustion Engines (ICE)

Appendix D Back up calculations

4.1 Appendix A

Drawings and data sheets

- O5-1008P-Worley Parsons, Process data for SCR unit
- Dwg. No. PGA1-PGA3, from BD Heat Recovery Div., Inc. Compact DeNOx systems, General Arrangement Drawings received from BHP.
- Layout Drawings:
  - Dwg. No. 05876-MA-001, Cabrillo Port FSRU, Main Deck, Overall layout
  - Dwg. No. PIP-2006-001, Overall plan and elevation, Cabrillo Port FSRU
  - Dwg. No. PIP-2006-002, Overall plan comparison, Cabrillo Port FSRU

4.2 Appendix B

References cited in the report

1. Neptune LNG Deepwater Port License Application, November 2006, Section 2, Detailed Description of the Project and Alternatives, pages 2-61 and 2-64.
2. David Hawkins, BD Heat Recovery Division, Inc., Operating Experience With an Integrated Selective Catalytic Reduction System (SCR) Operating with Submerged Combustion Vaporizers (SCV) at a North American Base Load Vaporization Facility, AIChE Spring National Meeting, April 2004
3. BD Heat Recovery Division, Inc. web site
4. Layout drawing transmitted to Aker Kvaerner by BHP Billiton (see Appendix A)
5. C.C. Yang and Zupeng Huang, Foster Wheeler North America Corporation, USA, Lower Emission LNG Vaporization, LNG Journal November/December 2004.
6. Mallinckrodt Chemicals MSDS for Sodium Carbonate
7. E-mail from Dave Hawkins (BD Heat) to Kamal Shah (Aker Kvaerner), October 31, 2006.
8. BASF product information sheet
9. Vaporizer data sheet, Selas Fluid Processing Corporation, Issue B, dated 2/18/05
10. E-mail communication with Mike Durilla, BASF
11. Aker Kvaerner Process Design Manual, Section 10.5.2.8 (See back-up calculations in Appendix D)
12. Aker Kvaerner PRV Relief Valve Calculations (see calculations in Appendix D)
13. OTC 17161, LNG Re-gasification Vessel – The First Offshore LNG Facility, Offshore Technology conference, Houston, Texas, 2005
14. Telephone conversation with Jonathan Lauck of Distrigas by Kamal Shah and John Siffert of Aker Kvaerner, Nov. 30, 2006

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4.3 Appendix C

Brochure for Wartsila Internal Combustion engines (ICE)

- Wartsila Brochure, 50DF engines
- Wartsila Brochure, The Enviro Concept
- Munters Diesel Emission Control, Drawing 182V-2

4.4 Appendix D

Back-up calculations

- Stack Temperature – Temperature rise, CO oxidation catalyst
- Tube rupture - Tube leak amount calculations
- EPA Spreadsheet for Cost Effectiveness Calculation
- FSRU hull extension cost estimate
- Calculated emission summary - NOx emission from SCV - 40 ppm
- Calculated emission summary - NOx emission from SCV – 20 ppm
- Calculated emission summary - NOx emission from SCV – 5 ppm